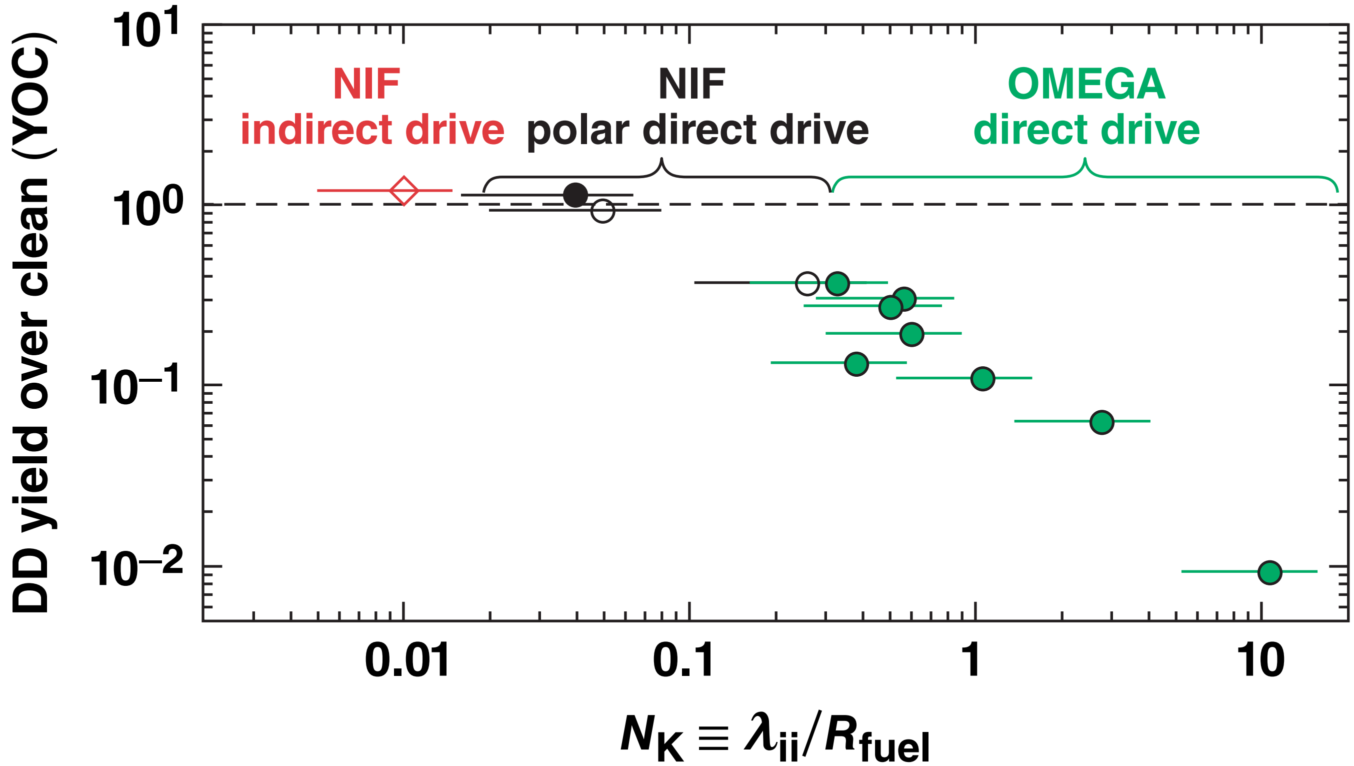
# Ion Kinetic Effects in Exploding-Pusher Implosions on OMEGA and the National Ignition Facility





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Summary

# Shock-driven implosion experiments deviate from hydro model predictions when the ion mean free path approaches the size of the implosion

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- Hydrodynamic assumptions can break down during the shock-convergence phase of both ablatively driven and shock-driven inertial confinement fusion (ICF) implosions, leading to ion kinetic effects
- Shock-driven experiments on OMEGA and the National Igntition Facility (NIF) show a strong trend of decreasing yield over clean (YOC) with increasing Knudsen number ($N_K = \lambda_{ii}/R_{fuel}$) for $N_K > 0.1$
- Ion diffusion and non-Maxwellian reduction of fusion reactivity are able to partially explain the results

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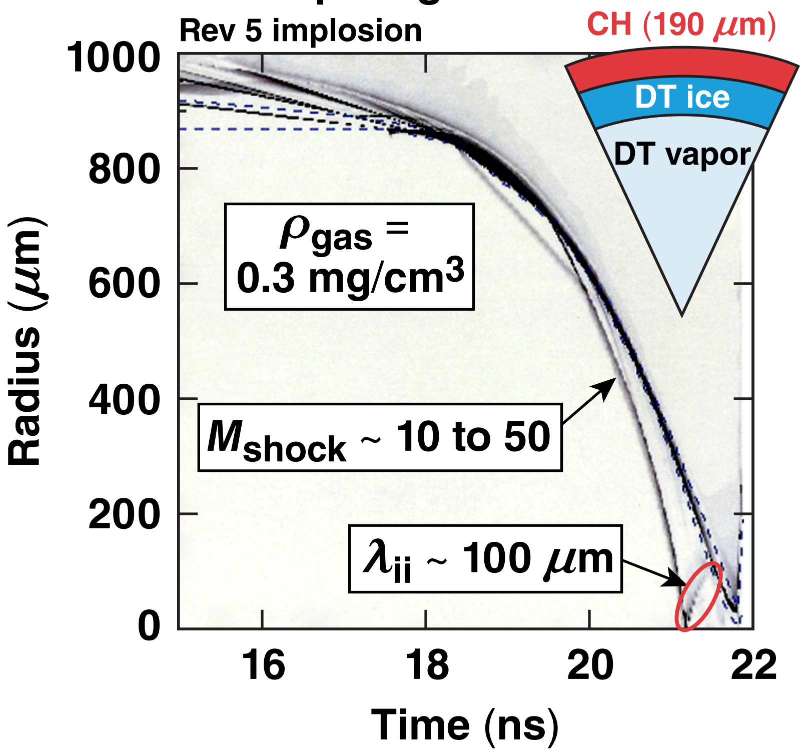
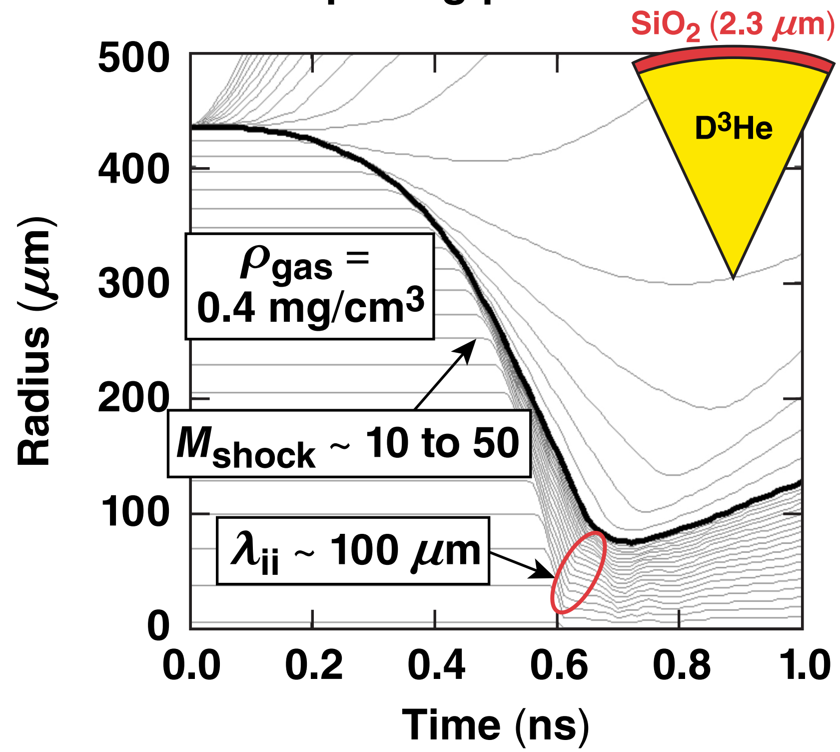
Motivation

# Exploding pushers generate kinetic conditions similar to the shock-convergence phase in hot-spot–ignition implosions

NIF hot-spot–ignition simulation*




OMEGA expoding-pusher simulation**




**In hot-spot ignition, the shock phase sets the initial hot-spot conditions prior to deceleration.**

* H. Robey
** A. Zylstra (*HYADES*)

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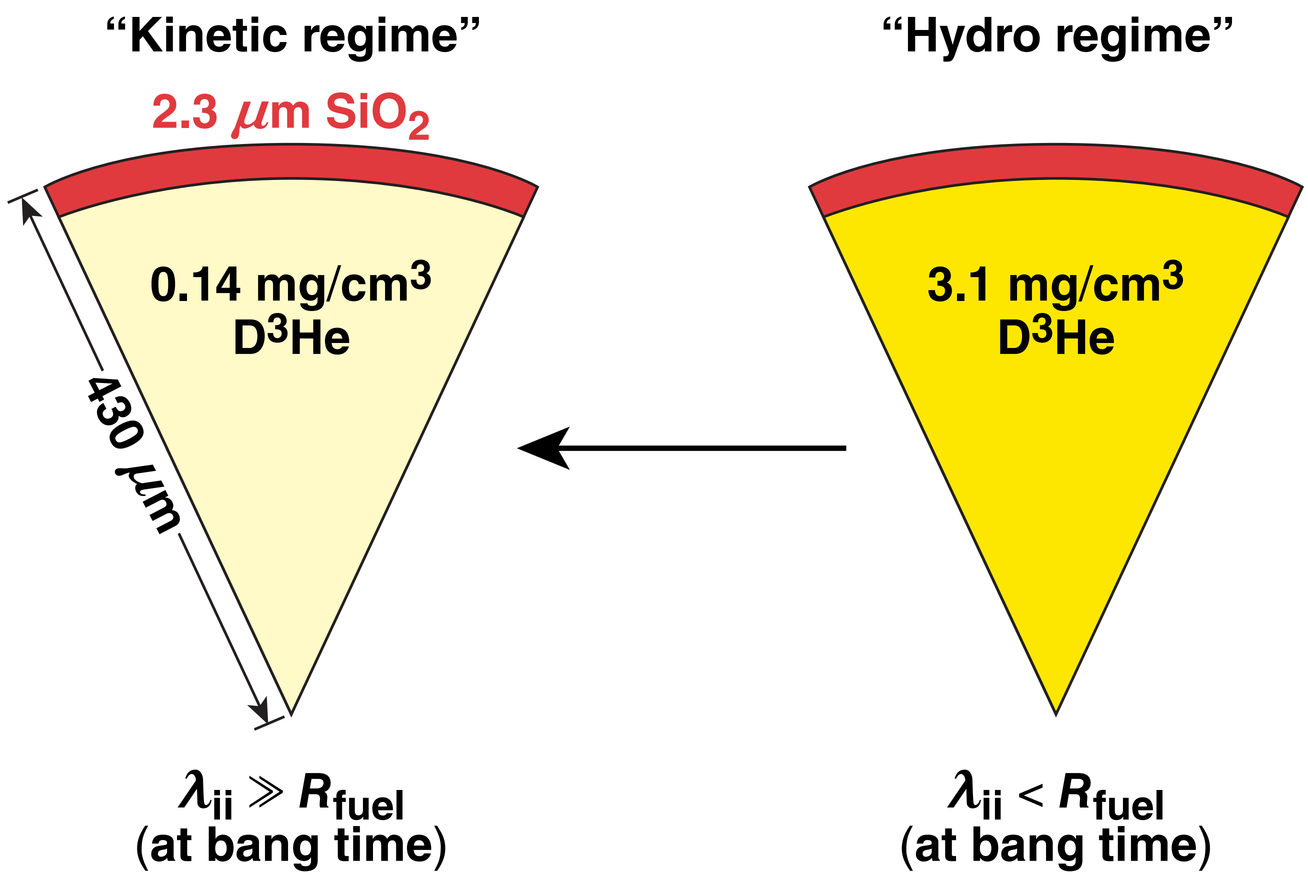
# A fuel-density scan in OMEGA $D^3He$-filled exploding pushers was used to isolate and study ion kinetic effects




**These experiments attempt to identify the conditions under which hydro models break down.**

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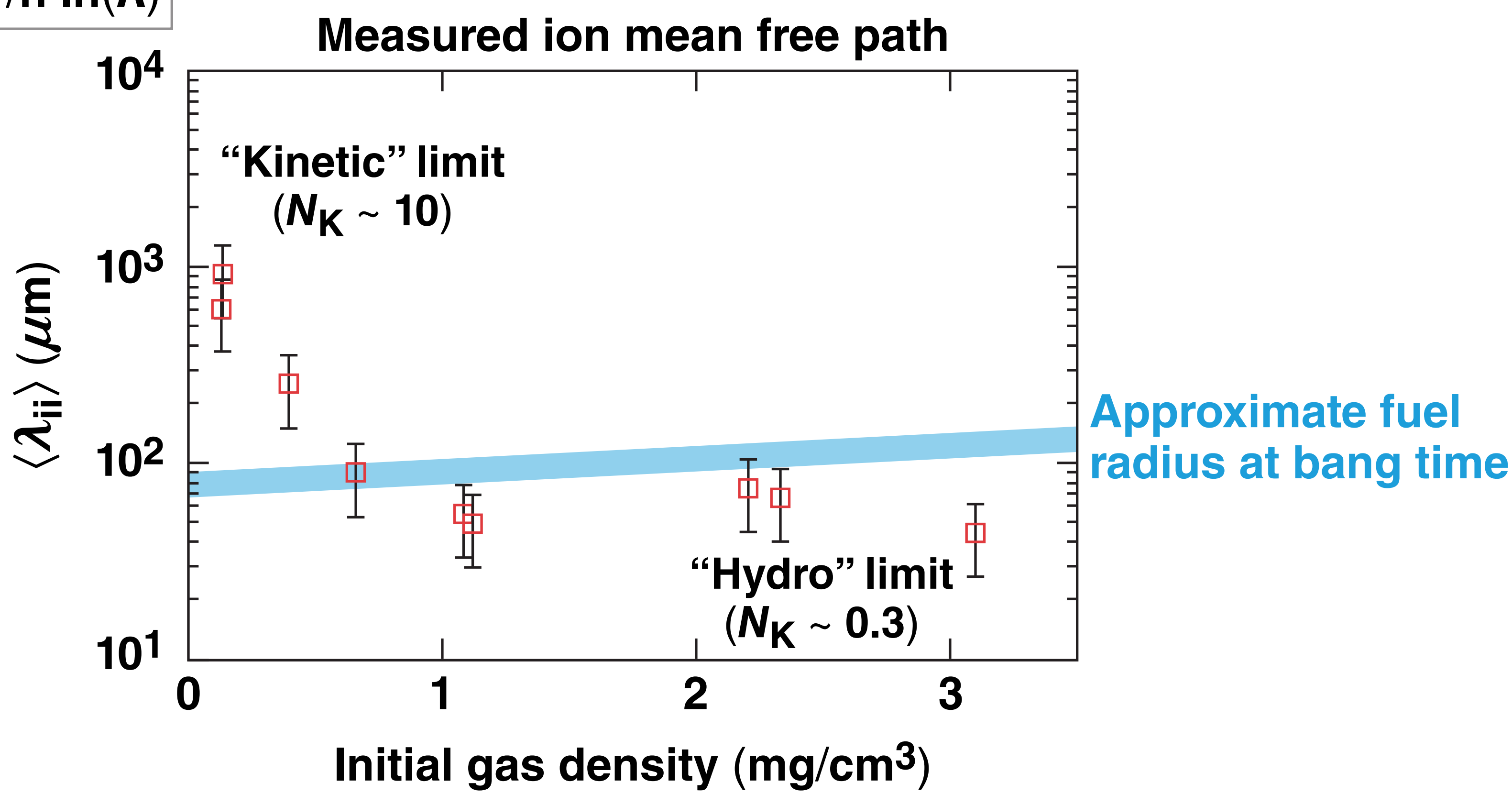
M. J. Rosenberg *et al.,* Phys. Rev. Lett. 112, 185001 (2014).

# As $\rho_{gas}$ is decreased, $\lambda_{ii}$ increases from ~50 $\mu$m to ~1000 $\mu$m and $N_K = \lambda_{ii}/R_{fuel}$ increases from ~0.3 to 10

$\lambda_{ii} \sim T_i^2/n \ln(\Lambda)$




**Implosions spanned the "strongly kinetic" to "hydrodynamic-like" regimes.**

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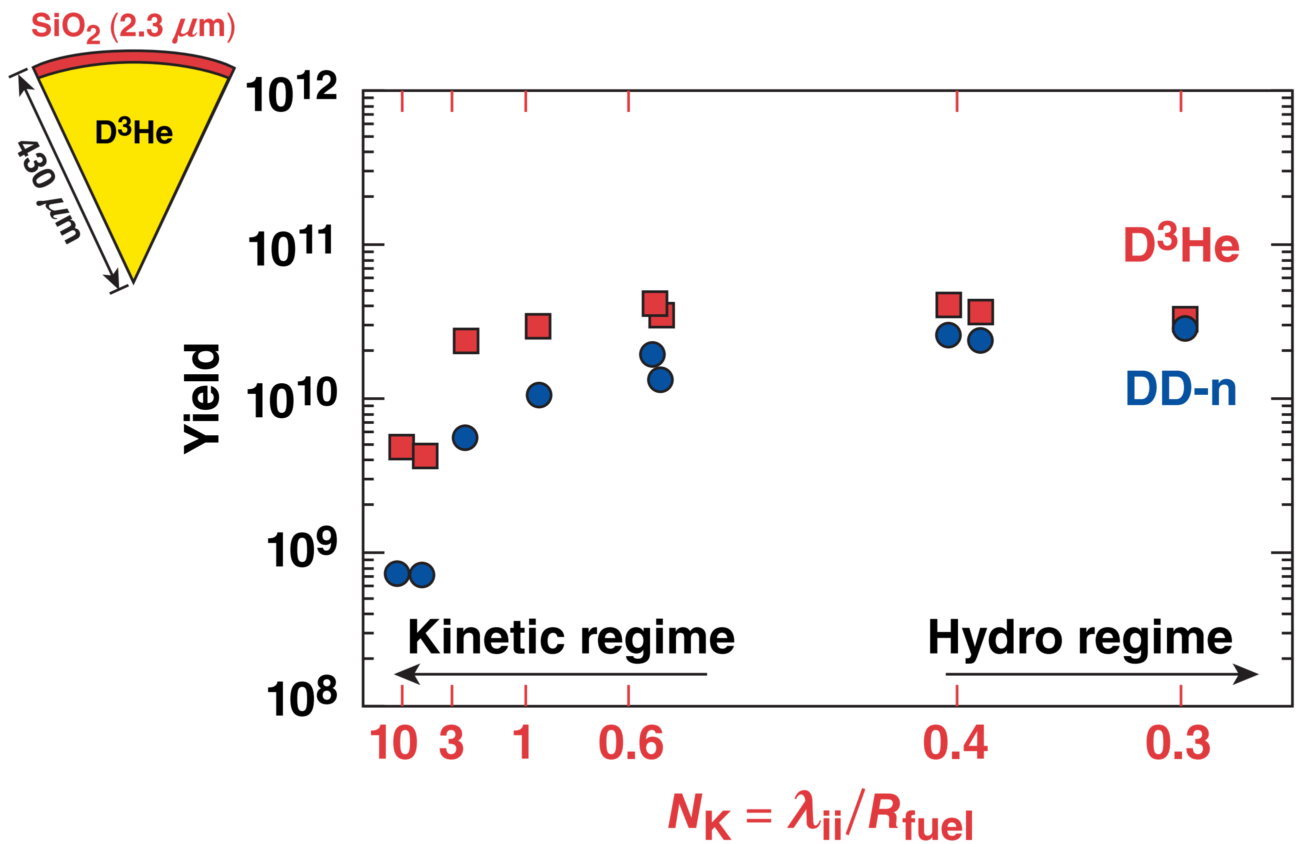
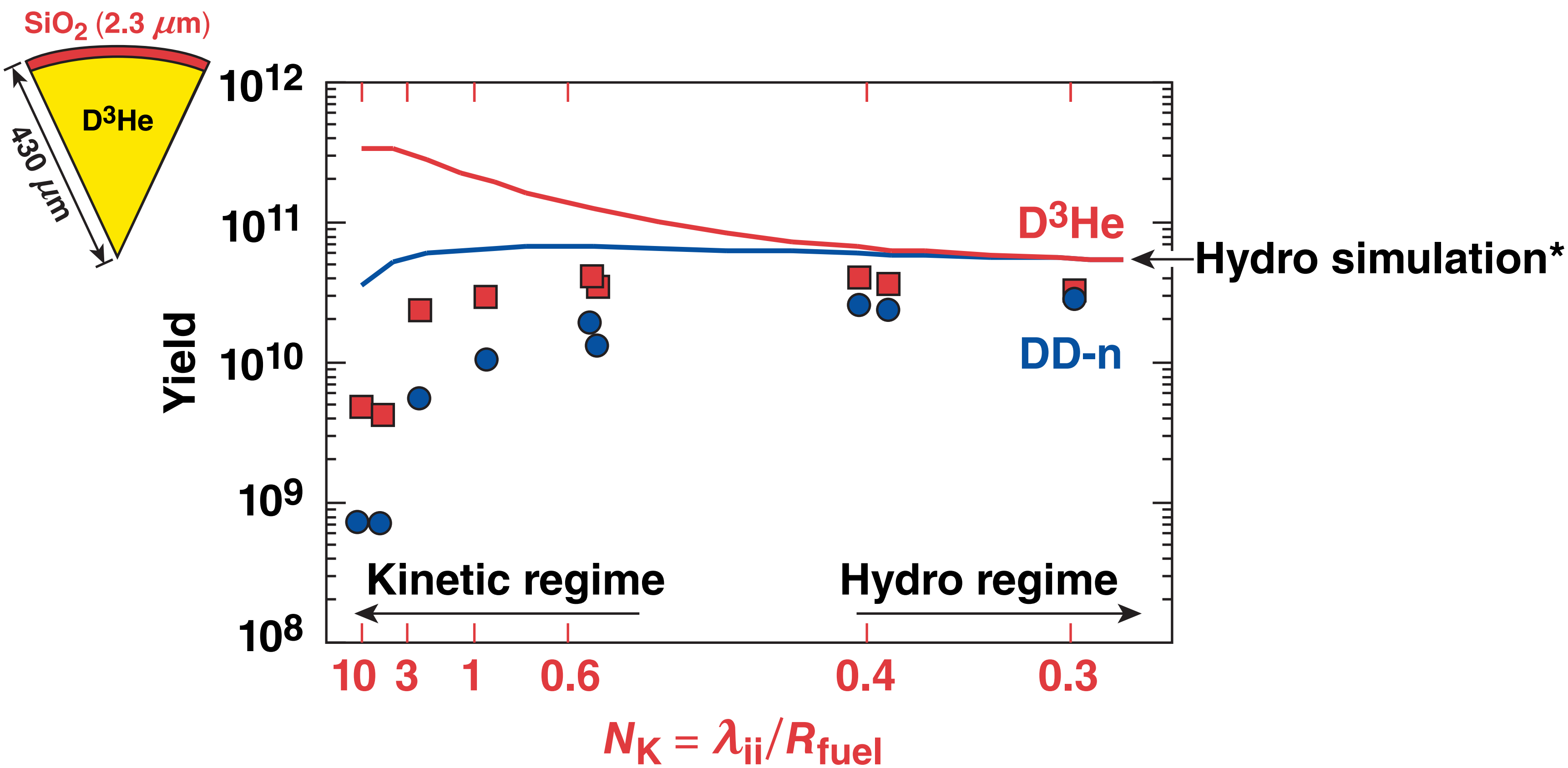
# Measured DD and $D^3He$ yields are found to drop off sharply in the high-$N_K$/kinetic limit



# Hydrodynamic simulations increasingly deviate from the data in the kinetic regime




*Simulations by N. M. Hoffman, LANL

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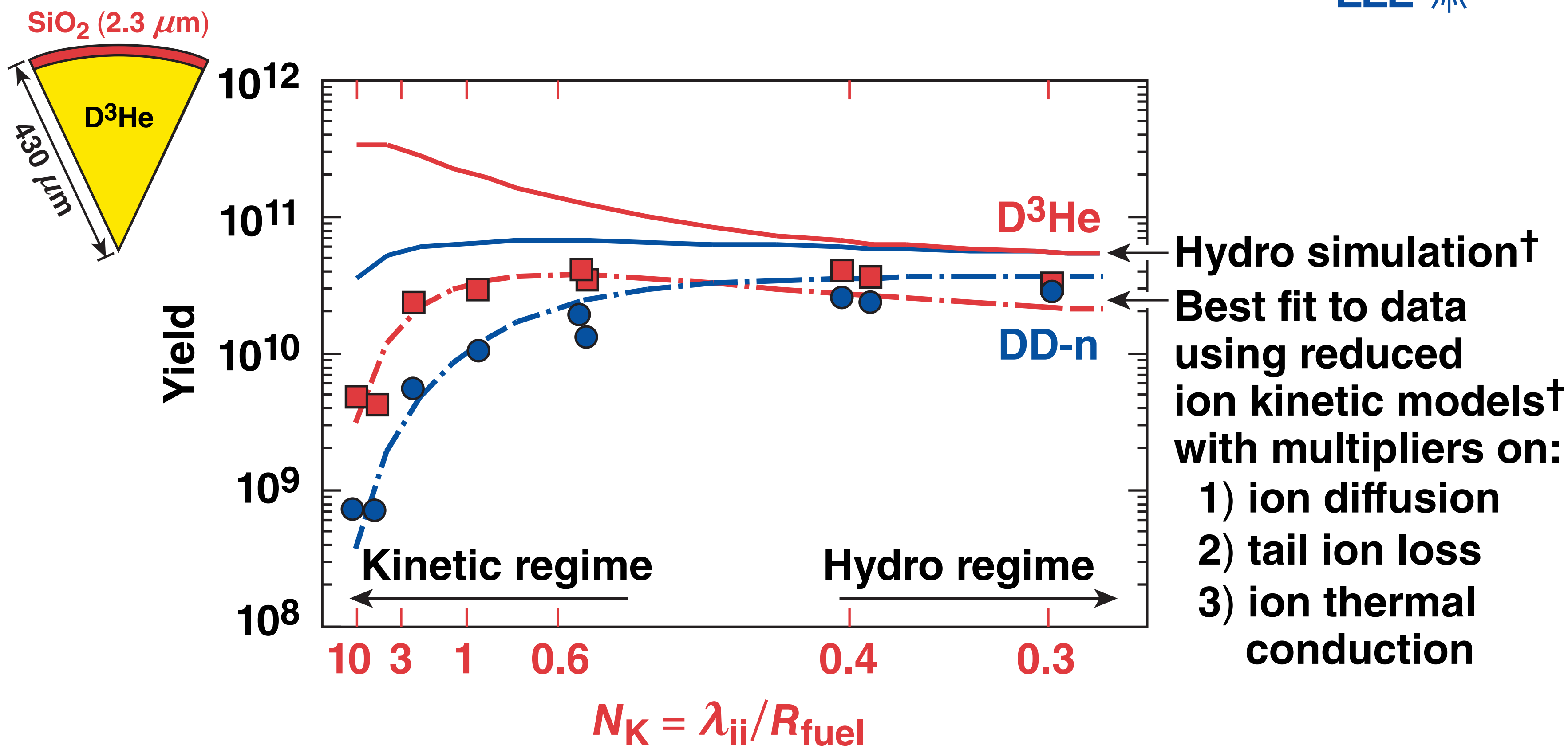
# Including "reduced ion kinetic"* models in a hydro simulation brings modeled yields into better agreement with the experiment




**Reduction of fusion reactivity because of non-Maxwellian tail ion loss** and ion diffusion are inferred to be significant.**

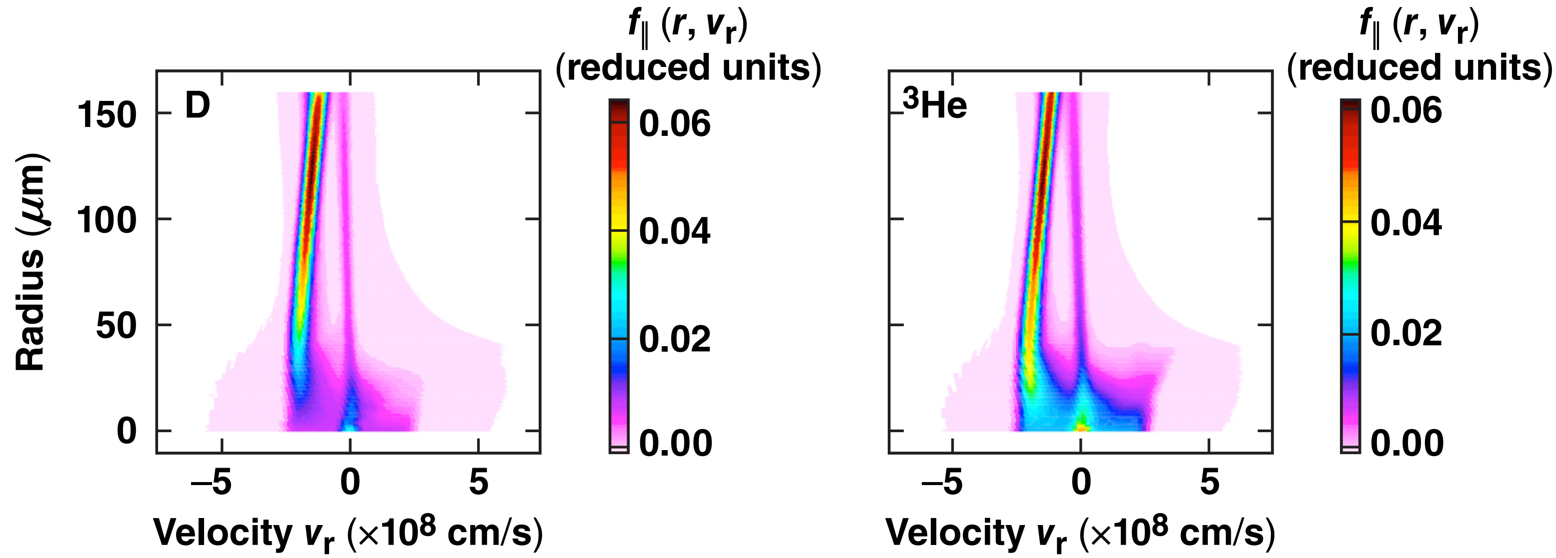
*N. M. Hoffman *et al.*, Phys. Plasmas 22, 052707 (2015).
**K. Molvig *et al.*, Phys. Rev. Lett. 109, 95001 (2012); B. J. Albright *et al.*, Phys. Plasmas 20, 122705 (2013).
†Simulations by N. M. Hoffman, LANL

E24401b

# For a first-principles kinetic approach, Fokker–Planck modeling using *FPION** has been performed

*FPION* simulations**

- Are initiated based on profiles from *HYADES* hydrodynamics simulations
- Model the gas region of the exploding-pusher implosion
- Show improved agreement in yield and ion temperature relative to pure hydro modeling and evidence of kinetic processes (e.g., counterstreaming ions)




**These simulations do not yet model the shell, so they do not account for ion diffusion across the fuel/shell interface.**

*O. Larroche, Eur. Phys. J. D 27, 131 (2003). **Simulations by O. Larroche, CEA
†O. Larroche *et al*., Phys. Plasmas 23, 012701 (2016).

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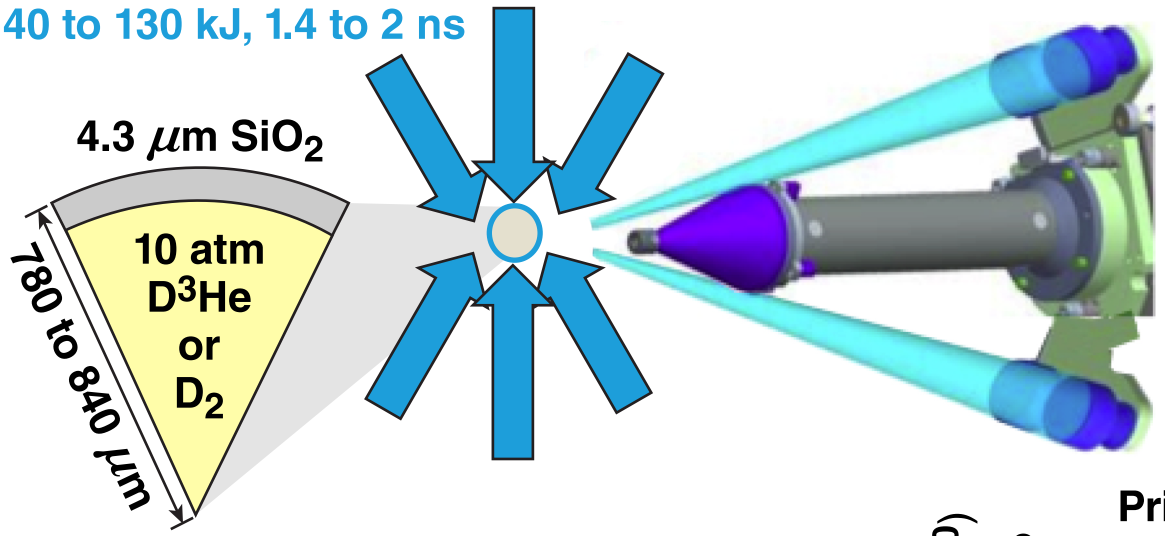
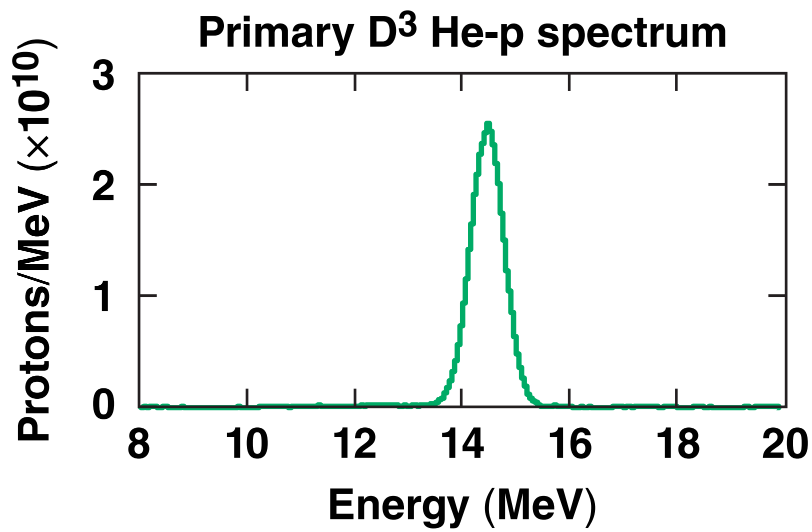
# Polar-direct-drive exploding pushers on the NIF were also studied to investigate ion kinetic effects

40 to 130 kJ, 1.4 to 2 ns




**NIF exploding pushers provide access to the low-$N_K$ regime in shock-driven implosions.**




* M. J. Rosenberg *et al*., Phys. Plasmas 21, 122712 (2014).

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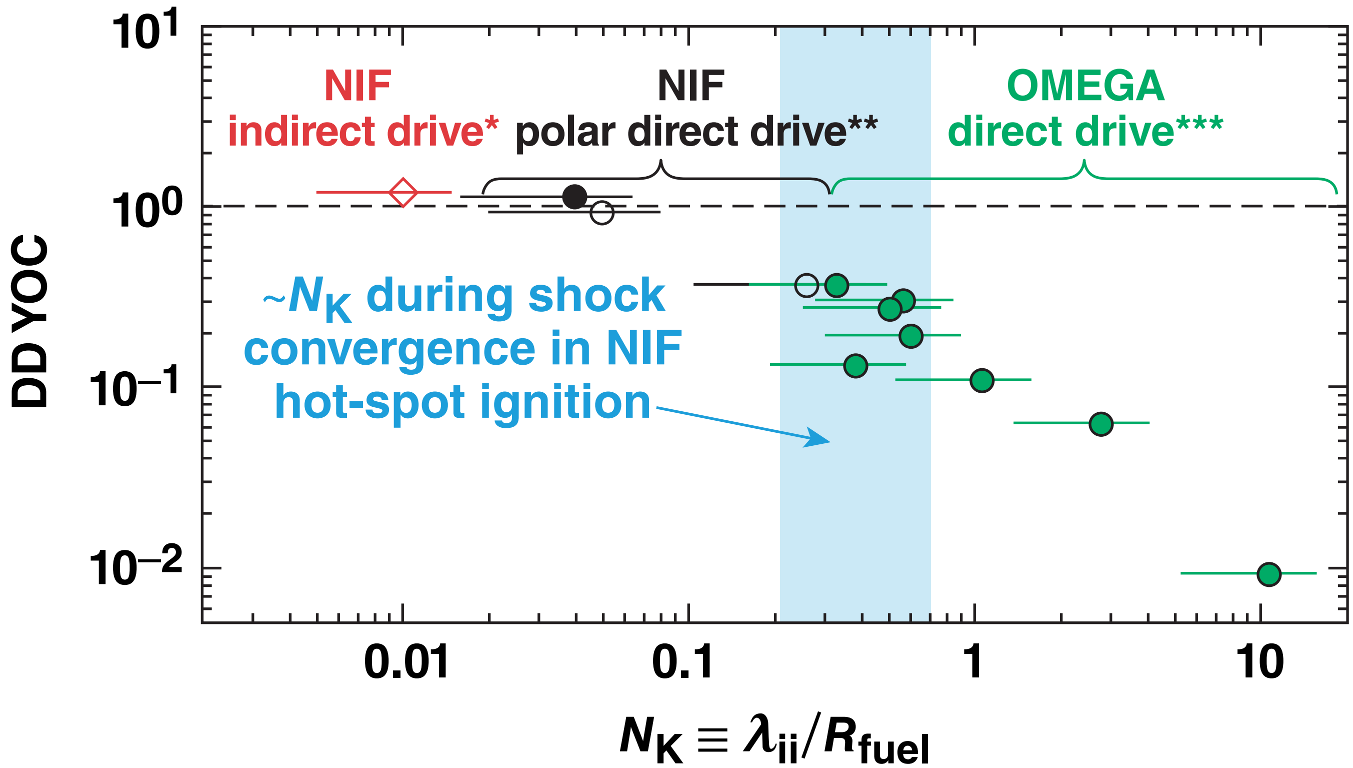
# Exploding pushers on the NIF and OMEGA show a unified trend of decreasing DD YOC with increasing $N_K$




**Shock-convergence phase of hot-spot ignition implosions is in a regime where kinetic effects start to become prevalent.**

* Compared to *HYDRA*, S. Le Pape *et al*., Phys. Rev. Lett. 112, 225002 (2014).
** Compared to *DRACO*, M. J. Rosenberg *et al*., Phys. Plasmas 21, 122712 (2014).
*** Compared to *DUED*, M. J. Rosenberg *et al*., Phys. Rev. Lett. 112, 185001 (2014).

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# Future work should investigate how these shock-phase ion kinetic effects can impact hot-spot formation and the subsequent compression phase

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- These data demonstrate that ion kinetic effects are likely to be prevalent in the hot spot shortly after shock convergence
  - mechanisms: diffusion or free streaming of thermal or suprathermal hot gas ions into the cold fuel? Perturbation of hydro profiles in initial hot spot?
- Focused experiments should aim to identify/decouple the critical mechanisms to provide a more-stringent test for models
  - CD/$^3$He in exploding pushers to benchmark ion diffusion models
  - high-precision fusion product spectroscopy to infer tail ion loss?
- We can use exploding-pusher data to benchmark models of these kinetic effects as applied in hydrocodes (e.g., *RIK*) or in first-principles kinetic simulations (e.g., *FPION*)
- These codes can then predict the impact of these kinetic effects on the evolution of the hot spot in ignition-relevant implosions

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# Shock-driven implosion experiments deviate from hydro model predictions when the ion mean free path approaches the size of the implosion

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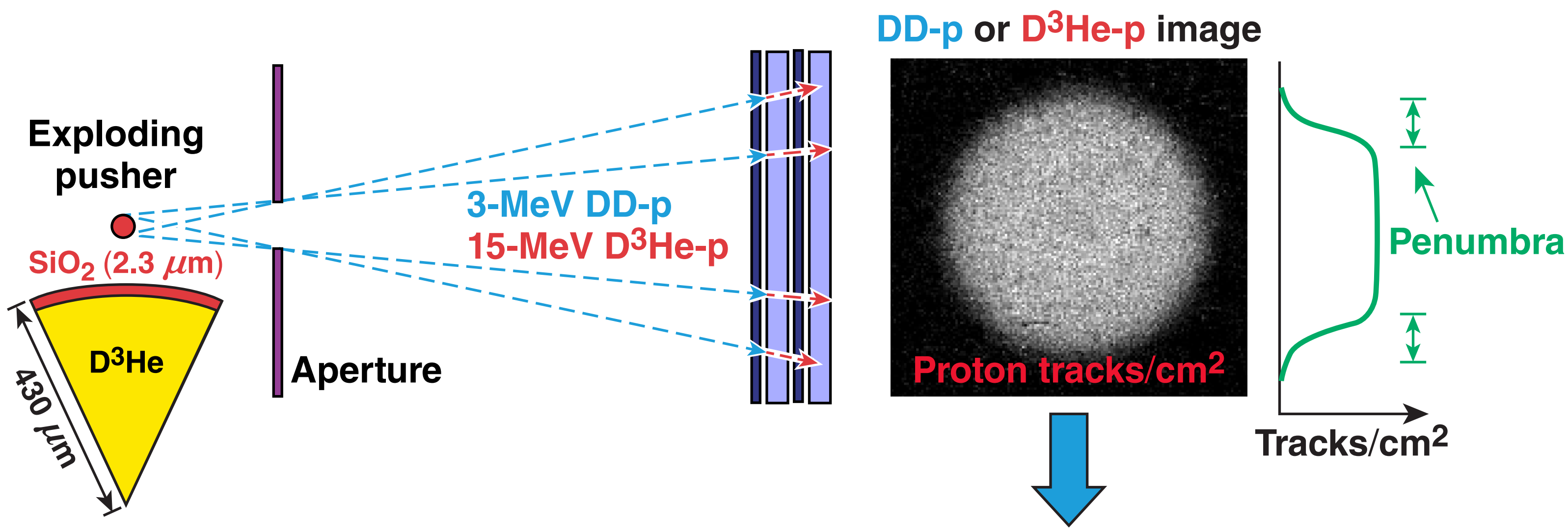
# Appendix

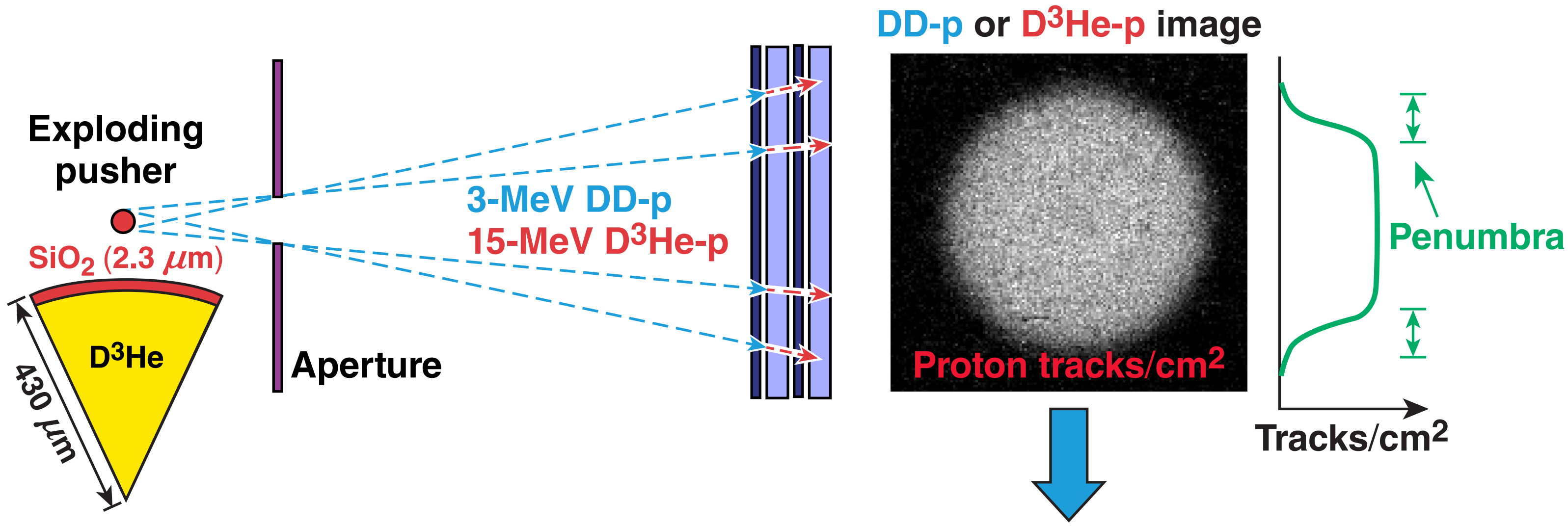
# To better understand ion kinetic effects, penumbral imaging of DD and $D^3He$ reactions was used to infer burn profiles



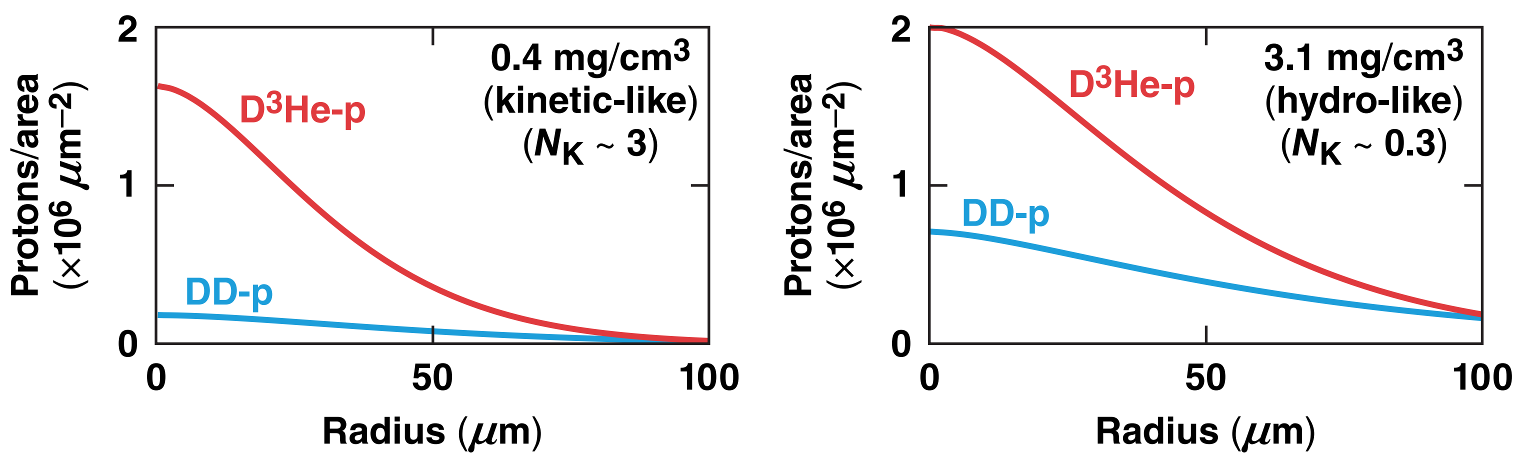

Reconstruct profiles of surface brightness of proton emission at the implosion


M. J. Rosenberg *et al*., Phys. Plasmas 22, 062702 (2015).
Penumbral imaging technique:
F. H. Séguin *et al*. Rev. Sci. Instrum. 75, 3520 (2004);
F. H. Séguin *et al*. Phys. Plasmas 13, 082704 (2006).

# To better understand ion kinetic effects, penumbral imaging of DD and $D^3He$ reactions was used to infer burn profiles




Surface brightness profiles of proton emission (forward fit to data)

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# In the “kinetic” regime, measured spatial burn profiles are centrally peaked, in stark contrast to a pure-hydro model

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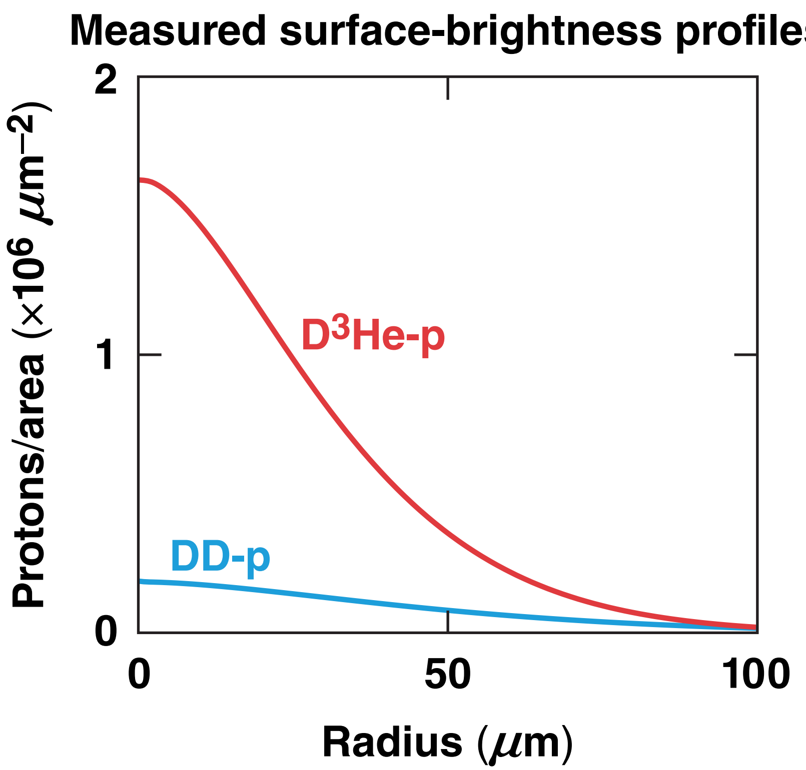
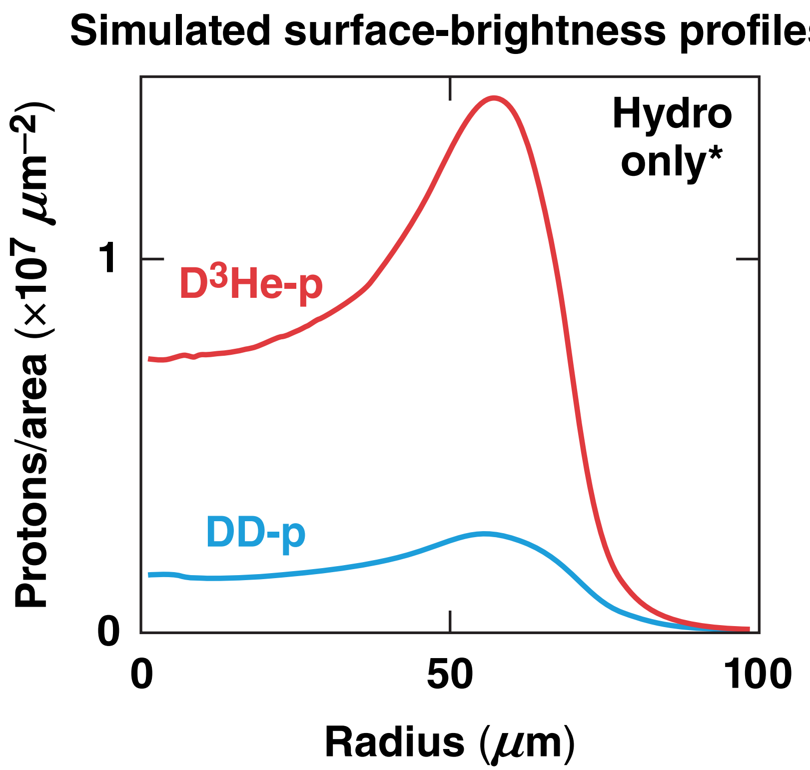
0.4 mg/cm$^3$ (kinetic regime, $N_K$ ~ 3)




*Simulations by P. Amendt, LLNL

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# Inclusion of ion diffusion recovers the centrally peaked burn profiles that were observed experimentally

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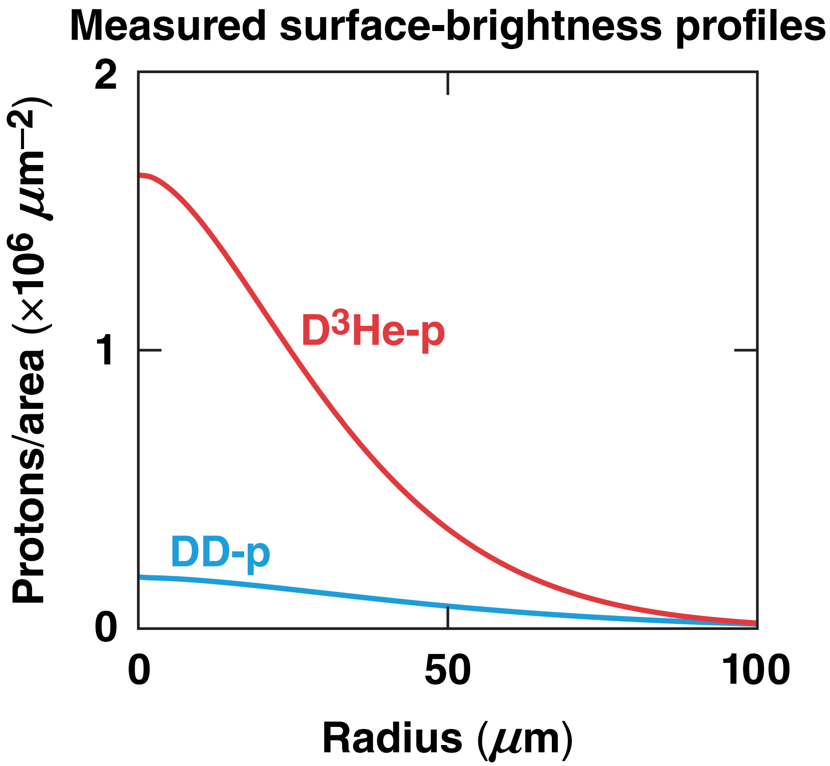
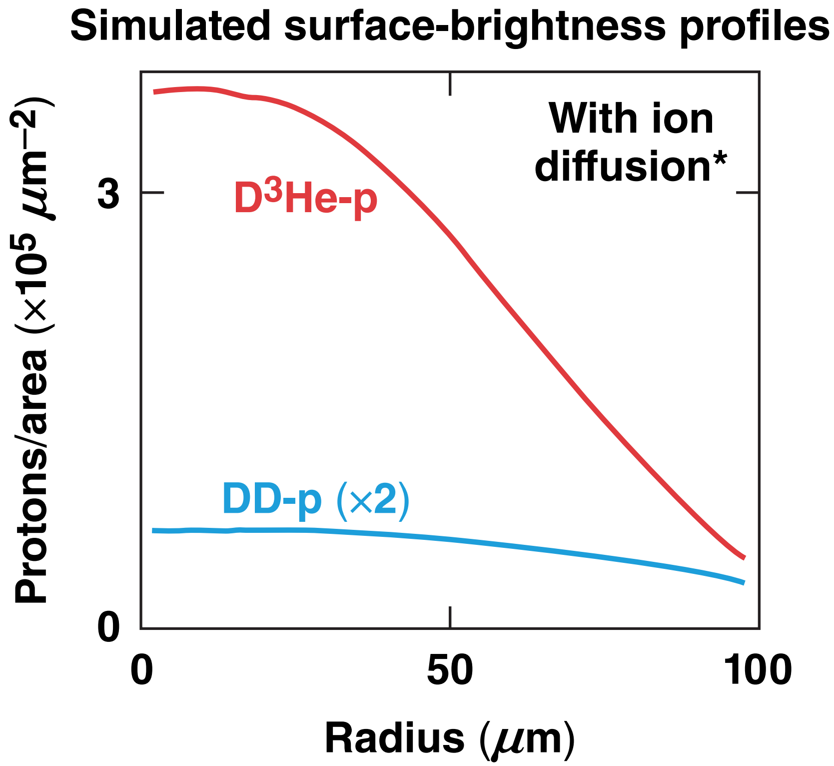
0.4 mg/cm$^3$ (kinetic regime, $N_K \sim 3$)




**Ion diffusion causes significant escape of fuel ions and penetration of shell ions into the fuel.**

* R. W. Schunk, Rev. Geophys. Space Phys. 15, 429 (1977); Simulations by P. Amendt, LLNL

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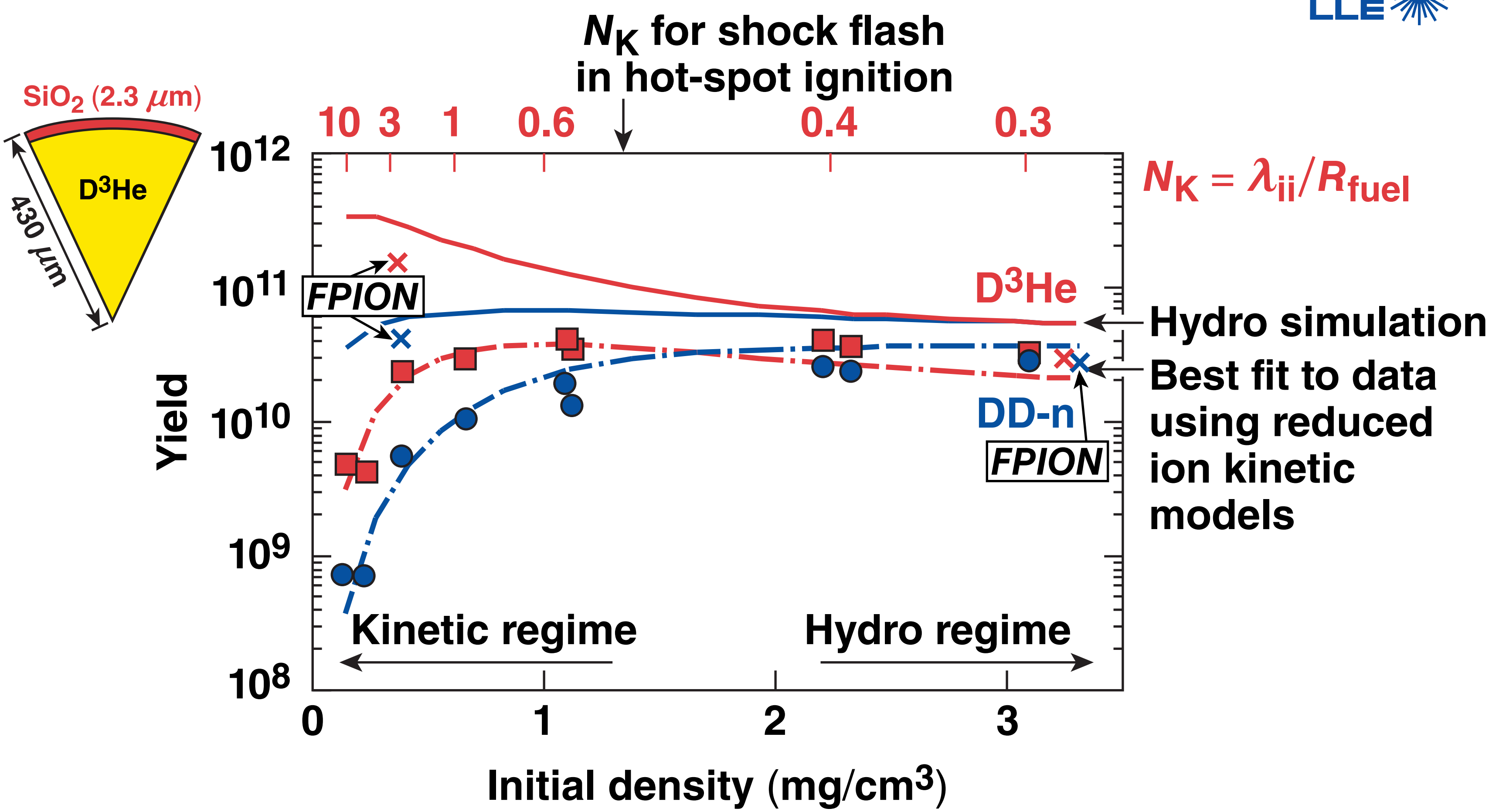
# The first kinetic (*FPION*) simulations of the gas region, initiated from *HYADES* profiles, show improvement over hydro modeling




These simulations do not yet model the shell, so they do not yet include ion diffusion.

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Simulations by O. Larroche, CEA